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# ASSORTATIVE MATCHING WITH LARGE FIRMS:

## Span of Control over More versus Better Workers\*

JAN EECKHOUT<sup>†</sup> AND PHILIPP KIRCHER<sup>‡</sup>

This Version – February 2012

### Abstract

In large firms, management resolves a trade off between hiring more versus better workers. The span of control or size is therefore intimately intertwined with the sorting pattern. This is important for macro and cross-country comparisons of productivity, for applications in international trade, and for labor markets. We analyze the worker assignment, firm size, and wages. The sorting *assignment* between workers and firms is governed by an intuitive cross-margin-complementarity condition that captures the complementarities between qualities (of workers and firms), and quantities (of the work force and firm resources). A simple system of two differential equations determines the equilibrium *firm size* and *wages*. More productive firms are larger if their advantage to increase the span of control (the firm type-workforce size complementarity) outweighs the workers' relative advantage of the use of firm resources (the worker type-firm resource complementarity).

*Keywords.* Span of Control. Sorting. Firm Size. Wage Distribution. Unemployment. Two-Sided Matching. Supermodularity.

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<sup>†</sup>University College London and ICREA-UPF, [j.eeckhout@ucl.ac.uk](mailto:j.eeckhout@ucl.ac.uk).

<sup>‡</sup>Department of Economics, London School of Economics and University of Pennsylvania, [P.Kircher@lse.ac.uk](mailto:P.Kircher@lse.ac.uk).

# 1 Introduction

Span of control – the number of workers under the control of management within a firm – attributes an essential role to the firm in economics. In the canonical macroeconomic context, firms predominantly make quantity decisions. Endowed with different management, technologies, or capital, companies choose the span of control accordingly, and this has important implications for the size of firms, as first pointed out by Lucas (1978). This labor factor intensity decision is both realistic and a convenient modeling device. It has been invoked to explain differences between countries (Restuccia-Rogerson, 2008), and to analyze technology adoption in evolving firms (Mortensen-Lentz, 2005, Jovanovic, 1982).

Yet, firms typically face a more complex tradeoff. They simultaneously choose the *quality* of the workers as well as the quantity. Heterogeneity in skills and jobs is without doubt an important component of the labor market. The allocation process of differently skilled workers to jobs has extensively been analyzed, both with search frictions and without.<sup>1</sup> In the standard frictionless matching model (Becker, 1973), each firm consists of exactly one job, just as in most of the matching models with search frictions.<sup>2</sup> This leads to sorting since the firm’s choice is in effect about *which* worker to hire – the extensive margin –, rather than how many – the intensive margin.

The aim of this paper is to investigate sorting in an otherwise conventional macro environment where the firm simultaneously choose the quality as well as the quantity of the work force. This provides a much richer role for the firm and its span of control or size. For example, we shed light on why the high skilled upper management in firms like Walmart have an enormous span of control over relatively low skilled workers, while in mom-and-pop retail stores the span of control is small and skills of both managers and workers are average. Or, what are the consequences of information technology that improves the ability to manage many workers, such as monitoring and GPS tracking devices? These example illustrate that we can address general questions: Are more productive firms larger? Do they hire better workers; or both? How does this affect managerial compensation and firm profits? And how does it depend on the particular industry and country we are considering?

We formalize the tradeoff between the intensive and the extensive margin in a very simple framework. Firms differ in the quality of their endowment, such as managerial skill in a modern economy or quality of their arable land in an agrarian economy. In the spirit of the previous work in this literature, firms compete in the same industry and produce a homogeneous output good, but nevertheless the best firms do not employ all the labor because of decreasing returns. With homogeneous workers, this replicates the Lucas model with an intensive margin only. Better firms have a comparative advantage and span their control over more workers. With heterogeneous workers, a firm simultaneously chooses the worker type and its span of control. If decreasing returns are so stark that each firm optimally chooses only one worker, then the model replicates the standard Beckerian matching model. Only the extensive margin matters and all firms have the same size. The general specification gives rise to a rich but tractable framework to study the interaction between firm size and the skill of the workforce.

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<sup>1</sup>The canonical matching model has also extensively been used in the international trade literature, see amongst others Grossman and Maggi (2000), Grossman (2004) and Costinot (2009).

<sup>2</sup>Amongst many others, see Burdett and Coles (1997) and Shimer and Smith (2000).

The paper contributes to existing work in four ways. First, we ask which workers are hired by which firms. We find a surprisingly simple condition for assortative matching that captures both the quality and quantity considerations. This condition is new and compares the different degrees of complementarity<sup>3</sup> along four margins: (1) *type complementarity* captures the interaction between firm and worker types. Clearly, if better firms receive an exceptionally high return only from better workers, then they will end up hiring those workers. This is the only effect present in standard quality-sorting models in the spirit of Becker (1973). Additionally, there is the (2) *complementarity in quantities* of workers and resources, just as in the standard model with quantity choices only. There is the (3) *span-of-control complementarity* between the firm or manager type and the number of workers that features in Lucas (1978); how much of a higher marginal product do better managers have from supervising more workers of a given skill? Finally, there is the (4) *managerial resource complementarity*, the complementarity between worker skills and managerial or firm resources: do better workers have a higher marginal product of receiving more supervision time? A simple tradeoff between these four forces determines the pattern of sorting. It characterizes the efficient equilibrium outcome and is a measure of the efficiency losses that would result from misallocation.

Second, we can precisely pin down the composition of the work force within different firm types, i.e., how firms resolve the tradeoff of span of control over more versus better workers. The equilibrium allocation of types and quantities is entirely governed by a simple system of two differential equations. In particular, this gives a prediction for the firm's span of control, and therefore, for the firm size distribution. For example under positive assortative matching, better management supervises larger groups (better firms are larger) provided the span of control complementarity (3) outweighs the managerial resource complementarity (4).

Even if the theory is very stylized, it allows us to revisit our example of the retail industry where high productivity companies such as Walmart have high skilled management and hire many mainly low skilled workers, compared to the smaller mom and pop stores. This indicates negative sorting together with a size distribution that exhibits a density of workers that is increasing in firm productivity. In the light of our theory, this is consistent with a type complementarity (1) that is small in this industry, whereas the span of control complementarity (3) is large: while the complementarity between managers and workers is small, at the margin management in better firms is much better at managing large groups than the low productivity firms. This may be the case for example because cash registers and inventories are nearly trivial to operate, while the firm heavily invests in management and control tools that allow the supervision of many workers through centralized information on performance on all registers and inventories. Not only does this lead to negative sorting, but also to a sharply increasing firm size in productivity, thus creating very large firms at the top. They do not need to spend much time with each employee because supervision time does not increase productivity much, and they have the tools to supervise many. Instead, in management consulting, with strong complementarities in manager and

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<sup>3</sup>We will use the term complementarity and supermodularity interchangeably. For our purposes, it can best be thought of as the fact that the marginal contribution of higher input (quantity or quality) to output is higher when matched with other high inputs, i.e. there are synergies. In mathematical terms, the cross-partial of the output generated is positive (negative in the case of substitutes or submodularity).

subordinate skill ((1) large) but moderate span of control technologies ((3) moderate), there is positive sorting. Top firms are only larger than bottom firms if their span of control (3) outweighs the benefits from training and interacting with employees (4). Given that the two counteract, top consulting firms tend to be only moderately larger than other firms in the industry.

The Walmart example clearly illustrates that their way of doing business is very different from how the retail sector worked half a century ago. Over time, information technology and investment in knowledge dramatically changes the production process. We can therefore analyze how technological change affects the firm size distribution and the composition in the work force. Skill-biased technological change is usually viewed as a change that makes the complementarity between worker skill and firm technology larger. But much of technological change is in terms of information technology that changes the complementarity between manager skill and the amount of workers he supervises. In this model, increases in (3) change the sorting pattern, but in particular it spreads out the firm size distribution. Big firms become even bigger relative to the small firms.

These insights on firm size, wages, and sorting patterns are captured in conditions that are sufficiently simple to suggest that the model might be a useful building block in future work. It captures as a special case the specific production structure of Garicano (2000), which has been fruitfully applied in the context of international trade and offshoring (e.g., Antràs, Garicano and Rossi-Hansberg (2006)). While international trade applications are beyond the scope of the present paper, we hope that our approach will prove useful for studying how both the size and the work-force skills of heterogeneous firms change when international integration changes the market structure. In our setting the size of the firm is limited by decreasing returns to scale in production due to scarce managerial resources, which offers a complimentary channel to the usual Dixit-Stiglitz reasoning based on limited demand for each variety (e.g., Costinot, 2009). Our model can be studied without functional form assumptions, yet it can also be integrated into a Dixit-Stiglitz type framework, as we show in our extensions. There we also show how unemployment can be introduced in our two-sided matching framework, which again has attracted recent interest in trade settings (e.g., Helpman, Itskohki and Redding (2011)).<sup>4</sup> And our approach might prove useful to understand cross-country differences in total factor productivity, which Restuccia-Rogerson (2008) and Hsieh-Klenow (2010) attribute to firm heterogeneity in conjunction with Lucas' span of control. By introducing worker heterogeneity and sorting in this otherwise standard model, the debate can be illuminated taking into account differences in skill distributions across countries, on top of the size distribution across firms.

The paper contributes to existing work in a third way. We integrate labor market frictions into the model by means of directed search. The general setup is sufficiently flexible to allow for us to introduce directed search frictions in the presence of sorting. We show that irrespective of the sorting pattern, unemployment rates are lower for more skilled workers, which is consistent with the empirically observed unemployment patterns. Instead, the vacancy rates across firm productivity levels is ambiguous. It

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<sup>4</sup>In Helpman, Itskohki and Redding (2011) firms are heterogeneous and also workers draw a heterogeneous match quality once they meet a firm, but in their setting workers are ex-ante identical and earn identical expected-payoffs since heterogeneity only arises as a shock, while in many trade settings we would like to start from a situation where workers of different types exist in the population.

depends on how firm size varies, which in turn is governed by the strength of the span of control complementarity relative to the managerial resource complementarity.

As a final contribution, we point out that our theory provides a unifying framework for previous models, most of which are special cases of ours. Clearly, Becker (1973) and Lucas (1978) are special cases. A general setup was also proposed in Rosen (1982), but solved only for a functional form that is a special case of our model, that of efficiency units of labor. Our setup also includes as special or limiting cases the functional forms of several existing models in this line of research such as Sattinger (1975), Garicano (2000), Antràs, Garicano and Rossi-Hansberg (2006), and Van Nieuwerburgh and Weill (2010). We can also adjust the setup to match the features of the Roy model (Heckman and Honore, 1990). Here we consider the competitive equilibrium outcome of the general model.

It should be noted that our setup is not restricted to the interpretation of span of control. For example, agricultural firms whose capital is land of different soil quality and who assign plots to workers of different endurance, or production firms whose capital is in its specific projects and who have to determine how many of these are handled by each of their workers.<sup>5</sup>

## Related Literature

Our model relates to several strands of existing literature. Here we single out the following four most relevant ones. Once we have laid out the model and derived the results, we discuss more formally in Section 3.3 how our framework captures and extends a number of the existing models in the literature that we mention here. In particular, there we make explicit the way in which those can be viewed as special cases of our setup.

1. The most common one-to-one matching models originating from Kantorovich (1942), Koopmans and Beckmann (1957), Shapley and Shubik (1971), and Becker (1973), restrict attention to settings where agents have to be matched into pairs, with the obvious limitation that they do not provide insights into the size of the firm and the capital intensity. This is a special case of our model with extreme decreasing returns. Notice that the matching models by Terviö (2008, and Gabaix and Landier (2007) to explain the changes of CEO compensation are of this kind. While they use firm size to determine the type of firm, only one worker (the CEO) is matched to one firm. A number of both early and recent contributions have focussed on environments where managers can supervise more than one worker. In Sattinger (1975), each employed worker type produces one unit of output, but requires supervision-time that depends on the manager type in a decreasing relation. A related structure arises in Garicano (2000) and Antràs, Garicano and Rossi-Hansberg (2006). Both models have the feature that both the quantity and quality of workers play a role, but in a rather stark manner where additional supervision time above the minimum has no additional benefits. Their conditions again arise as limiting cases of our model.

Rosen (1982) proposes a general setup with worker heterogeneity, where quantity and quality interact

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<sup>5</sup>Instead of projects, the capital may be their clients, and the decision is how many clients to assign to a member of the sales force of a given ability. Such capital is specific to the firm. In an extension we also accommodate generic physical capital on top of the differentiated firm-specific capital.

multiplicatively, which is a special case of ours. Rosen never solves his general setup, but assumes a functional form that guarantees perfect substitutability, i.e., workers of a given type generate exactly the same output as twice as many workers of half that type. This assumption is now commonly known as efficiency units of labor, and it is well-known that it generates no sorting implications.

**2.** While the assortative matching literature has made rather specific assumptions for multi-worker firms that we attempt to generalize, the combinatorial matching and general equilibrium literature has instead stayed general but focusses mainly on existence theorems rather than on characterizing the sorting or the wage patterns. The classic example in the combinatorial matching literature is Kelso and Crawford (1982), who propose a many-to-one matching framework in a finite economy and allow for arbitrary production externalities across workers in the same firm. While it is well-known that the stable equilibrium or the core may not exist, they derive a sufficient condition for existence, that of gross substitutes. This condition means that adding another worker decreases the marginal value of each existing worker. This condition is satisfied in our setting since output is assumed to be concave in the number of workers. Gul and Stacchetti (1999) analyze the gross substitutes condition in the context of Walrasian equilibrium and show existence and the relation between the Walrasian price and the payment in the Vickrey-Clarke-Groves mechanism. In the context of auction design, Milgrom and Hatfield analyze package bidding as a model of many to one matching.

**3.** Our model differs from settings such as the Roy (1951) model and its recent variants in e.g., Heckman and Honore (1990) where each firm (or sector) can absorb unbounded numbers of agents. In our setup marginal product decreases as any particular firm gets extensively large. Some models combine the Roy model with a demand by consumers that entails a constant elasticity of substitution (CES), which implies that the price falls when more workers produce output in a particular sector (see recently Costinot (2009)). The difference is that in such settings no agent internalizes the fact that the price falls when more output is produced. In our settings the firms understand that output falls when they produce more. In the final examples we also allow for a CES demand structure, but now this results in a model of imperfect competition similar to Dixit and Stiglitz (1977), only that now two-sided heterogeneity and an extensive margin are allowed.

**4.** Finally, the extension to search frictions is linked to recent developments in the literature. In one-to-one matching, sorting has been integrated in models of search, see for example Shimer and Smith (2000), Shi (2001), Shimer (2005), Atakan (2006), and Eeckhout and Kircher (2010). Also firm size has in different ways been modeled in the canonical search framework. The key challenge has been the wage setting mechanism. Smith (1999) resolves this with multi-agent sequential Nash Bargaining, whereas Hawkins (2011) and Kaas and Kircher (2011) determine market prices by means of wage posting and directed search. We use the latter. The real novelty of our approach here relative to the existing search literature is to combine *both* sorting under two-sided heterogeneity *and* firm size. This allows us to provide general conditions on the variation of the unemployment rate by skills and the vacancy rate by firm size. This is important for the estimation of search models using matched employer-employee data that feature both sorting and firm size variation.

## 2 The Model

We consider a static assignment problem in the tradition of Monge-Kantorovich and where the allocation is not limited to one-to-one matching.

*Agents.* The economy consists of heterogeneous firms and workers. Workers are indexed by their skill  $x \in \mathcal{X} = \mathbb{R}_+$ , and  $H_w(x)$  denotes the measure of workers with skills below  $x$ . Also firms are heterogeneous in terms of some proprietary input into production that is exclusive to the firm, such as scarce managerial talent or particular proprietary capital goods. In a modern business setting, this is the time endowment of an entrepreneur that he spends interacting with and supervising his employees. In an agricultural economy this is the amount of land that an agricultural firm possesses. Firms are indexed by their productivity type  $y \in \mathcal{Y} = \mathbb{R}_+$ , where  $H_f(y)$  denotes the measure of firms with type below  $y$ . Unless otherwise stated, we focus on distributions  $H_f$  and  $H_w$  with non-zero continuous densities  $h_f$  and  $h_w$  on a compact subset  $[\underline{x}, \bar{x}] \subset \mathcal{X}$  and  $[\underline{y}, \bar{y}] \subset \mathcal{Y}$ , respectively, but especially for our main characterization result we also provide a proof for arbitrary distribution functions.

*Preferences and Production.* Firms and workers are risk-neutral expected utility maximizers. The main primitive of our model is the output function  $F : \mathbb{R}_+^4 \rightarrow \mathbb{R}_{++}$  that describes how the firm combines labor and its resources to produce output. If a firm of type  $y$  hires an amount of labor  $l_x$  of type  $x$ , it has to choose a fraction of its proprietary resources  $r_x$  that it dedicates to this worker type. This allows the firm  $y$  to produce output

$$F(x, y, l_x, r_x)$$

with this worker type  $x$ , where the first two arguments  $(x, y)$  are *quality variables* describing the worker and firm types while the latter two arguments  $(l, r)$  are *quantity variables* describing the level of inputs. We assume that total resources at the firm level  $r$  are fixed. Without loss we can therefore normalize  $r = 1$ .<sup>6</sup> The firms can allocate resources over different skilled worker types  $x$  as long as its choice  $r_x$  satisfies the feasibility constraint  $\int_{\mathcal{X}} r_x dx = 1$ .

We will focus on a particular class of functions  $F$ , where the output of each worker depends only on his own type  $x$ , the type of the firm  $y$ , and the factor intensity  $r_x/l_x$  that each of the workers obtains. Total output  $F$  then has constant returns to scale in the quantity variables: output doubles when both the quantity of resources and of workers are doubled. We retain the assumption of constant returns to scale in the quantity variables throughout. Therefore, if we denote  $\theta_x = l_x/r_x$ , we can write output per  $r_x$  units of resources as<sup>7</sup>

$$f(x, y, \theta) := F(x, y, l_x/r_x, 1).$$

If a firm hires only one worker type, the unit endowment of resources means that total output is  $f$  and

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<sup>6</sup>If instead  $r$  exogenously depends on  $y$ , our analysis goes through for a function  $\tilde{F}(x, y, l, r) = F(x, y, l, r(y))$  after a change of variables. Below in section 4.2, we analyze the case where  $r$  is endogenous.

<sup>7</sup>If  $F(x, y, l, r)$  has constant returns to scale, we can write it as  $F = rF(x, y, l/r, 1)$  and define  $f(x, y, l/r) := F(x, y, l/r, 1)$  as the output per unit of resource. Alternatively, we can write it as  $F = lF(x, y, 1, r/l)$ , so that  $g(x, y, r/l) = F(x, y, 1, r/l)$  represents the output per worker. In our exposition we work with the former, ie, from the firm's perspective, which is convenient in many derivations.



its third argument represents the firm's size. We also assume that  $F$  is twice continuously differentiable, and that it is strictly concave in each of the quantity variables. Even though we often refer to higher types as "better" types, we do not need to make any assumptions with respect to the quality variables except twice-differentiability to obtain our results.

Finally, for a firm that hires several worker types we assume that its total output is the sum of the outputs across all its worker types: firm  $y$ 's total output is  $\int F(x, y, l_x, r_x) dx$ . This is an important assumption because it rules out complementarities between different worker types. The motive for this assumption is tractability. Abstracting from this one source of complementarity is obviously restrictive. It does allow us to solve the model<sup>8</sup> and make progress in analyzing all the other cross-complementarities between quantities and qualities.

*Competitive Market Equilibrium.* We consider a competitive equilibrium where firms can hire a worker of type  $x$  at wage  $w(x)$ . In equilibrium, their hiring decisions must be optimal and markets for each worker type must clear.

Firm optimality in a frictionless competitive market requires that a firm of type  $y$  maximizes its output minus wage costs as follows:

$$\max_{l_x, r_x} \int [F(x, y, l_x, r_x) - w(x)l_x] dx \quad (1)$$

where  $r_x$  can be any probability density function over  $x$ . Factoring out  $r_x$  from the square bracket reveals that the interior depends only on the factor intensity  $\theta = l_x/r_x$ , which can be freely chosen at any level in  $\Theta = \mathbb{R}_+$  by adjusting the labor input appropriately. Because output across different types is additive, optimality requires that the firm places positive resources only on combinations of  $x \in \mathcal{X}$  and  $\theta \in \Theta$  that solve<sup>9</sup>

$$\max_{x, \theta} f(x, y, \theta) - \theta w(x). \quad (2)$$

If there is only one such combination that solves this maximization problem, then the firm will hire only one worker type, allocate all resources to this type, and hire an amount of labor  $l = \theta$ . Both firms and workers can abstain from the market and obtain a payoff normalized to zero, which means that profits and wages cannot fall below this level.<sup>10</sup>

Feasibility of the allocation implies that firms attempt to hire no more workers than there are in the population. Denote by  $\mathcal{R}(x, y, \theta)$  the resource allocation in the economy, which describes the amount of resources that firms with a type below  $y$  devote to workers of a type below  $x$  that are employed with a factor intensity  $l_x/r_x \leq \theta$ . We use the convention that  $\mathcal{R}(x, y, 0) = 0$ .<sup>11</sup> Let  $\mathcal{R}(y|\mathcal{X}, \Theta)$  denote the

<sup>8</sup>Several difficulties to solve the model arise, eg, those due to non-existence as pointed out by Kelso and Crawford (1982).

<sup>9</sup>Problem (1) is equivalent to  $\max_{r(\cdot)} \int (r_x \max_{\theta_x} [F(x, y, \theta_x, 1) - w(x)\theta_x]) dx$ , where  $\theta_x = l_x/r_x$  can be adjusted through appropriate hiring of workers. Clearly, resources are only devoted to combinations of  $x$  and  $\theta$  that maximize (2).

<sup>10</sup>This is indeed simply a normalization. Consider true outside options  $o(x)$  and  $q(y)$  for firms and workers and output function  $\tilde{F}(x, y, l_x, r_y)$ . These can be incorporated into our framework by considering a normalized production function of form  $F(x, y, l_x, r_y) = \tilde{F}(x, y, l_x, r_y) - l_x o(x) - r_y q(y)$  that captures the loss in outside option due to matching.

<sup>11</sup>This implies that firms that do not want to hire any worker ( $\theta = 0$ ) are counted as "unmatched" rather than employing

marginal over  $y$  when the other two variables can take any value in their type space. It denotes the amount of resources used by firms with type below  $y$ . Similarly, let  $\mathcal{R}(\theta, x|\mathcal{Y})$  be the resources spent by all firms on workers of with type  $x$  employed with intensity less than  $\theta$ . Weighted by the intensity this yields the number of workers hired, so  $\int_{\Theta} \theta d\mathcal{R}(\theta, x|\mathcal{Y})$  gives the number of workers hired with type up to  $x$ . Feasibility requires that these cannot exceed the number of agents in the population, ie, for all  $y' < y$  and  $x' < x$  we have

$$\mathcal{R}(y|\mathcal{X}, \Theta) - \mathcal{R}(y'|\mathcal{X}, \Theta) \leq H^f(y) - H^f(y') \quad (3)$$

$$\int_{\Theta} \theta d\mathcal{R}(\theta, x|\mathcal{Y}) - \int_{\Theta} \theta d\mathcal{R}(\theta, x'|\mathcal{Y}) \leq H_w(x) - H_w(x'). \quad (4)$$

We can now define an equilibrium as follows:

**Definition 1** *An equilibrium is a tuple  $(w, \mathcal{R})$  consisting of a non-negative hedonic wage schedule  $w(\cdot)$  and a feasible resource allocation  $\mathcal{R}$  such that*

1. *Optimality:  $(x, y, \theta) \in \text{supp} \mathcal{R}$  only if it satisfies (2).*
2. *Market Clearing: (4) holds with equality if wages are strictly positive on  $(x', x]$ .<sup>12</sup>*

The market clearing condition simply states that if wages for some worker types are positive, their markets clear. Existence of an equilibrium when output is multiplicatively separable in quantity and quality variables and bounded has been proven, eg, in Jerez (2009). Her proof can also be extended to the general setting when output is bounded, and we provide a way to construct an equilibrium under our sorting condition. Our main focus in this work, though, is on characterization: When do better firms hire better workers? How are the wages determined? When are better firms employ more employees? How is that effected by quantity-biased technological change?

*Assortative Matching.* Let  $\mathcal{R}(x, y|\Theta)$  be the marginal distribution of  $\mathcal{R}$  over the firm and worker types at any level of intensity. It denotes the amount of resources devoted by firms with type below  $y$  to workers of skill below  $x$ , and we refer to it as the type allocation. Matching is positive assortative if  $(x, y)$  in the support of the type allocation implies that  $(x', y')$  is not in its support unless either both dimensions are weakly larger or both weakly smaller than  $(x, y)$ . This means that better firms hire better workers. Similarly, matching is negative assortative if  $(x, y)$  in the support of the type allocation implies that  $(x', y')$  is not in its support unless one dimension is weakly larger and one is weakly smaller than  $(x, y)$ . In such a case better firms hire lower worker types. For some derivations it will be particularly useful to focus on (strictly) differential assortativeness, where the support of  $\mathcal{R}$  is concentrated only on points  $(x, \mu(x), \theta(x))$  for some differentiable functions  $\theta$  and  $\mu$ , with the former strictly positive almost everywhere and the latter (strictly) monotone.

*Alternative interpretations of our setup.* In our exposition we assume that the number of firms is fixed, they each own a unit measure of a scarce resource and allocate it to the different workers that they

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zero workers of type  $x$ . This will only be important when we consider the definition of assortative matching.

<sup>12</sup>Formally: (4) holds with equality if wages are strictly positive  $H_w$ -almost everywhere on  $(x', x]$ .

hire. Only the workers are traded in the market. Think about managers, each of whom has one unit of time for supervision, and who hire workers.

It might be worthwhile to note that there are alternative ways to set up our model that lead to identical results for sorting and factor prices. In our setup, we assumed that firms "buy" workers at wage  $w(x)$ . We could have chosen a different setup where workers buy resources for production at some endogenous price schedule  $v(y)$ . It turns out that our equilibrium profits according to (2) coincide with the equilibrium price  $v(y)$  that arises in the alternative model where workers buy resources.

Finally, we could assume that there are both resource owner and workers, and both workers and resources are traded in the market at endogenous prices  $v(y)$  and  $w(x)$ , respectively. Both workers and resources can be put together to produce output. Anybody can set up a production entity and make profits

$$\max_{x,y,l,r} F(x,y,l,r) - lw(x) - rv(y),$$

which in equilibrium has to equal zero due to free entry, and demand has to equal supply of both workers and resources. Again, in equilibrium of this alternative model the wages are the same as in our equilibrium and the price of resources equals the firms' profits in our setup. In fact, this setup is identical to ours, only that we assumed that unit measure of resources are tied to a particular manager who runs the firm and reaps as profits the price of his resource.

Even within our exposition the production function can be interpreted in broader terms. First, we interpreted  $r$  as the fraction of the firm's resources, implicitly using a unit measure of resources for each firm. This is natural in the example of managerial time, but in many other settings firms differ in their endowments. It turns out that this easily captures in our setting, since the unit restriction in terms of resources is a normalization.<sup>13</sup> We can also accommodate a setting where firms can acquire additional resources.<sup>14</sup>

Additionally, one might want to follow many macroeconomic models and include some kind of generic capital good that can be bought in the world market for price  $i$  per unit and enters the production function as another factor.<sup>15</sup> We return to this extension in Section 4. In Section 4.1 we also cover the case where firms have to post vacancies in a frictional (competitive) search market, and the firm has to determine how many vacancies to post in order to attract the right level workers into production. This framework also allows us to capture unemployed workers in a large firm model with heterogeneity.

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<sup>13</sup>If firms of type  $y$  have  $T(y)$  resources and produce  $\tilde{F}(x,y,l,t)$  by using  $t$  units of them, we can express this in terms of the fraction  $r$  of their resources:  $F(x,y,l,r) = \tilde{F}(x,y,l,rT(y))$ .

<sup>14</sup>If firms can create a unit of resources at cost  $c(y)$ , then in the ensuing equilibrium after resources are created the equilibrium profit per unit of resource of type  $y$  has to equal  $c(y)$ . It turns out that this makes it particularly easy to construct an equilibrium.

<sup>15</sup>If the firm buys  $k$  units generic capital and  $\tilde{F}(x,y,l,t,k)$  is the corresponding output, then the production function we analyze is the induced production after optimal decisions on generic capital are made:  $F(x,y,l,r) = \max_k \tilde{F}(x,y,l,r,k) - ik$ .

### 3 The Main Results

Models of assortative matching are in general difficult to characterize. Therefore, the literature has tried to identify conditions under which sorting is assortative. These conditions help our understanding of the underlying driving sources of sorting. In a setting like this where the welfare theorems hold, such conditions uncover the efficiency reasons behind the sorting patterns. And if the appropriate conditions are fulfilled, they substantially reduce the complexity of the assignment problem and allow further characterization of the equilibrium. In this section we derive necessary and sufficient conditions for assortative matching and characterize the assortative equilibrium.

#### 3.1 Assortative Matching

In order to build intuition for our main proposition, it will be useful to focus first on differential assortativeness which allows us to make the derivation of our main condition transparent. Assume that the equilibrium is assortative, supported by some differentiable assignment function  $\mu(x)$  and intensity  $\theta(x) > 0$ . By (2) this means that  $(x, \theta(x))$  are maximizers of the following problem for a firm of type  $y = \mu(x)$  :

$$\max_{x, \theta} f(x, y, \theta) - \theta w(x).$$

Assortative matching means that each firm only hires one type, and this problem can be understood as the problem of a firm that could choose any other worker type at any other quantity. As will become clear in the following, the wages are twice differentiable,<sup>16</sup> and the first order conditions for optimality are

$$f_{\theta}(x, \mu(x), \theta(x)) - w(x) = 0 \quad (5)$$

$$f_x(x, \mu(x), \theta(x)) - \theta(x)w'(x) = 0, \quad (6)$$

where  $\mu(x)$  and  $\theta(x)$  are the equilibrium values. The second order condition requires the Hessian  $\mathbf{H}$  to be negative definite:

$$\mathbf{H} = \begin{pmatrix} f_{\theta\theta} & f_{x\theta} - w'(x) \\ f_{x\theta} - w'(x) & f_{xx} - \theta w''(x) \end{pmatrix}.$$

This requires  $f_{\theta\theta}$  to be negative and the determinant  $|\mathbf{H}|$  to be positive, or

$$f_{\theta\theta}[f_{xx} - \theta w''(x)] - (f_{x\theta} - w'(x))^2 \geq 0. \quad (7)$$

We can differentiate (5) and (6) with respect to the worker type to get

$$f_{x\theta} - w'(x) = -\mu'(x)f_{y\theta} - \theta'(x)f_{\theta\theta} \quad (8)$$

$$f_{xx} - \theta(x)w''(x) = -\mu'(x)f_{xy} - \theta'(x)[f_{x\theta} - w'(x)]. \quad (9)$$

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<sup>16</sup>Given the assumed differentiability of  $\mu$  and  $\theta$ , the wage has to be differentiable as defined in (8) and (9) below.

In the following three lines we successively substitute (8), (9) and then (6) into optimality condition (7):

$$\begin{aligned} -\mu'(x)f_{\theta\theta}f_{xy} - [\theta'(x)f_{\theta\theta} + f_{x\theta} - w'(x)] [f_{x\theta} - w'(x)] &\geq 0 \\ -\mu'(x)f_{\theta\theta}f_{xy} + \mu'(x)f_{y\theta} [f_{x\theta} - w'(x)] &\geq 0 \\ -\mu'(x)[f_{\theta\theta}f_{xy} - f_{y\theta}f_{x\theta} + f_{y\theta}f_x/\theta] &\geq 0 \end{aligned}$$

For strictly positive assortative matching ( $\mu'(x) > 0$ ) it has to hold the the term in square brackets is negative, for strictly negative assortative matching the term in square brackets need to be positive. Focussing on positive assortative matching, and using the relationship in (6), we obtain the condition:

$$f_{\theta\theta}f_{xy} - f_{y\theta}f_{x\theta} + f_{y\theta}f_x/\theta \leq 0. \quad (10)$$

It turns out that this condition can more conveniently be summarized in terms of the original function  $F(x, y, r, s)$ , for which we know that  $F(x, y, \theta, 1) = f(x, y, \theta)$ . The following relationships will also prove useful. Homogeneity of  $F$  implies that  $-F_{34} = \theta F_{33}$ . Since  $F$  is constant returns, so is  $F_1$ .<sup>17</sup> A standard implication of constant returns it then  $F_1(x, y, \theta, 1) = \theta F_{13} + F_{14}$ . We can now rewrite (10) in terms of  $F(x, y, \theta, 1)$  and rearrange to obtain the following cross-margin-complementarity condition:

$$F_{33}F_{12} - F_{23} [F_{13} - F_1/\theta] \leq 0 \quad (11)$$

$$\Leftrightarrow F_{33}F_{12} + F_{23}F_{14}/\theta \leq 0$$

$$\Leftrightarrow F_{12}F_{34} \geq F_{23}F_{14} \quad (12)$$

So the condition depends on the cross-partials in each dimension, relative to the cross-partials across the two dimensions. Only if the within-complementarities in extensive and intensive deminsion on the left hand side exceed the between-complementarities from extensive to intensive margin on the right hand side does positive assortative matching arise. The following sums up this finding: A necessary condition to have equilibria with positive assortative matching is that (12) holds along the equilibrium path. The reverse inequality is necessary for negative assortative matching.

The preceeding argument heavily relied on local variations to establish the necessity of inequality (12). In the following we will show that one does not need any additional requirements to achieve assortative matching. Also, we will prove the proposition for arbitrary type distributions including those that might not have a continuous density.<sup>18</sup>

**Proposition 1** *Consider arbitrary type distributions. A necessary (sufficient) condition for some (all) equilibria to entail positive assortative matching under any type distribution is that the following in-*

<sup>17</sup>It holds that  $F(x, y, r, s) = sF(x, y, r/s, 1)$ , so differentiation implies that  $F_1(x, y, r, s) = sF_1(x, y, r/s, 1)$ .

<sup>18</sup>Also note that under homogeneity of degree one the condition  $F_{12}(x, y, l, r)F_{34}(x, y, l, r) \geq F_{23}(x, y, l, r)F_{14}(x, y, l, r)$  is equivalent to  $F_{12}(x, y, l/r, 1)F_{34}(x, y, l/r, 1) \geq F_{23}(x, y, l/r, 1)F_{14}(x, y, l/r, 1)$  when  $r > 0$  and  $l > 0$ , which means that less combinations have to be checked.

equality holds (strictly):

$$F_{12}F_{34} \geq F_{23}F_{14} \text{ for all } (x, y, l, r) \in \mathbb{R}_+^4. \quad (13)$$

The opposite inequality provides a necessary and sufficient condition for negative assortative matching.

**Proof.** The proof relies on the first welfare theorem. Since we have quasi-linear utility, any equilibrium maximizes the sum of outputs in the economy. A feasible distribution  $\mathcal{R}$  generates market output

$$S(\mathcal{R}) = \int F(x, y, \theta, 1) d\mathcal{R}.$$

In the appendix we prove sufficiency by considering the case where  $(x_i, y_i, \theta_i) \in \text{supp}\mathcal{R}$  for  $i \in \{1, 2\}$  and  $x_1 > x_2$  but  $y_1 < y_2$ . We establish that output is strictly increased under a feasible variation yielding resource allocation  $\mathcal{R}'$  that pairs some of the  $x_1$  workers to some of the  $y_2$  resources. Therefore,  $\mathcal{R}$  cannot be optimal and cannot be an equilibrium, implying that sorting must be positive assortative, which establishes sufficiency. Since we construct an improvement path, we require the condition to hold at all possible values (i.e., in  $\mathbb{R}_+^4$ ). A similar argument establishes that if (13) fails then any matchings within the type space where it fails have to be negative assortative, as otherwise re-arranging would improve output. So if (13) fails we can find some type distribution with types in the region where it fails such that we have negative sorting, which means that positive assortative matching cannot hold for all type distributions. This establishes necessity. An analogue argument establishes the results for negative assortative matching. ■

While the interpretation applies most generally, we like to think of the resources of a firm as the time spent by managers supervising other workers. Now one of the key determinants of positive/negative assortative matching is whether  $F_{14}$  is positive or negative. If managerial time is particularly productive when spent with high skilled types, then it is positive. If more managerial time is especially useful for the low skilled, then it is negative. Observe that this is a requirement for a given  $y$  and does not involve any variation in the managerial quality  $y$ . It is an empirical question whether it is positive or negative. To illustrate that  $F_{14}$  may be negative, a comparison can be insightful with the attention teachers pay to students. Typically, teachers will spend more time with the less gifted students rather than with the more gifted ones.

Interpreting this condition is relatively straightforward: On the left-hand side, a high cross-partial on the quality dimensions ( $F_{12}$ ) means that higher types have ceteris paribus a higher marginal return for matching with higher types on the other side. This is reinforced by a higher cross-partial on the quality dimension, even though under constant returns to scale this can be viewed as a normalization. More importantly is the interpretation of the terms on the right-hand side. Consider the cross-partial  $F_{23}$ . If this is high, it means that we are in a setting where higher firms have a higher marginal valuation for the quantity of workers. That is, better firms value the number of “bodies” that work for them especially high. In this case better firms would like to employ many workers, which favors those where which do not require many resources. If  $F_{14}$  is negative these are the high skilled workers and the right hand side favors positive assortative matching, while  $F_{14}$  negative means that these are the low skilled

workers which favors negative assortative matching.

The importance of the right hand side relies on the ability to substitute additional workers to make up for their lower quality. The discussion in Subsection 3.3 reveals that as the elasticity of substitution on the quantity dimension goes to zero in a way that agents can only be matched into pairs, the importance of the right hand side vanishes. It also discusses other settings from the literature that arise as special cases. Finally, one may wonder what happens when our non-homotheticity assumption does not hold and output is not proportional to the ratio  $\theta$  of the labor force  $l$  to the amount of resources  $r$ . Conceptually, the problem is identical to the one we solve here (see the Appendix for the derivation). While the interpretation is much less transparent<sup>19</sup>, the main sorting condition (11) is still necessary for differential positive assortative matching under increasing returns to scale, only the steps that require homogeneity do not apply.

### 3.2 Equilibrium Assignment, Firm Size Distribution and Wage Profile

In contrast to models with pairwise matching where assortativeness immediately implies who matches with whom (the best with the best, the second best with the second best, and so forth), this is not obvious in this framework as particular firms may hire more or less workers in equilibrium. In the appendix we show how to construct a differentiable positive assorted equilibrium when (13) holds on the full domain. Our main focus is the characterization. For the following we will consider output functions that are increasing in types, which ensures that all types above some cutoff are matched.<sup>20</sup> We

**Proposition 2** *If matching is differentially assortative and output is increasing in types, then the factor intensity, equilibrium assignment, and wages are determined by the following system of differential equations evaluated along the equilibrium allocation:*

$$\text{PAM:} \quad \theta'(x) = \frac{\mathcal{H}(x)F_{23} - F_{14}}{F_{34}}; \quad \mu'(x) = \frac{\mathcal{H}(x)}{\theta(x)}; \quad w'(x) = \frac{F_1}{\theta(x)}, \quad (14)$$

$$\text{NAM:} \quad \theta'(x) = -\frac{\mathcal{H}(x)F_{23} + F_{14}}{F_{34}}; \quad \mu'(x) = -\frac{\mathcal{H}(x)}{\theta(x)}; \quad w'(x) = \frac{F_1}{\theta(x)}, \quad (15)$$

where  $\mathcal{H}(x) = \frac{h_w(x)}{h_f(\mu(x))}$ .

**Proof.** Consider the case of PAM – the case of NAM can be derived in a similar way. The equilibrium condition for market clearing condition implies  $H_w(\bar{x}) - H_w(x) = \int_{\mu(x)}^{\bar{y}} \theta(\tilde{x}) h_f(\tilde{x}) dx$ . Differentiating with respect to  $x$  delivers the second differential equation in (14). The initial condition in the case of PAM

<sup>19</sup>At the moment we have entertained the notion that each worker interacts with the resources to obtain output. Just envision briefly a production technology that is customized such that for each worker type, output can be produced easier when there are more workers and resources of that type in the sense that the output function  $F$  has increasing returns to scale. Clearly, in this the restriction that each firm has a unit-measure of resources becomes binding: firms would ideally like to merge to larger entities. In many settings this might not be feasible, though, for example if a manager cannot expand the time he has available for supervision.

<sup>20</sup>If output can fall for higher types, holding all other variables constant, than there might be holes in the matching set, and the following characterization can only be applied on each connected component. The results holds even if output can fall, as long as it is ensured that on the equilibrium path all agents above some cut-off trade.

is  $\mu(\bar{x}) = \bar{y}$ . From (6) we know that  $w' = f_x/\theta$ , which gives the third equation since  $F_1 = f_x$ . From the first-order condition in equation (5) we know that  $f_\theta(x, \mu(x), \theta(x)) = w(x)$ . Then from equation (8), after substituting for  $w'$  and  $\mu'$  we obtain:

$$f_x/\theta = f_{x\theta} + f_{y\theta}/\theta + \theta' f_{\theta\theta}.$$

Using the same substitutions that we used in connection with equation (10) we obtain the first equation in (14). The initial condition for this differential equation obtains from running down the allocation from the top to the bottom and where the boundary condition holds either when the lowest type is attained or when the number of searchers goes to zero. An equilibrium allocation simultaneously solves the differential equation for  $\mu'$  and  $\theta'$  with the respective boundary conditions. ■

This gives an immediate proposition for the size of the different firms:

**Proposition 3** *Under differential assortative matching when output is increasing in types, better firms hire more workers if and only if along the equilibrium path:*

1.  $\mathcal{H}(x)F_{23} > F_{14}$  under PAM,
2.  $-\mathcal{H}(x)F_{23} < F_{14}$  under NAM.

**Proof.** This follows readily from Proposition 2, once one realizes that under NAM  $\theta'(x) < 0$ . ■

The result follows immediately from the Proposition, observing that  $F_{34} = -\theta F_{33}$  is strictly positive because of our concavity assumption, and that under NAM better workers are working for worse managers. The trade-off in the case of PAM is the following. Clearly, if better firms have a higher marginal value of hiring many workers ( $F_{23}$  large), this gives rise to better firms being large. Nevertheless, under assortative matching they also hire better workers. If these workers have a high marginal value from getting many resources of the firm ( $F_{14}$  large), then the firm will tend to be small. Clearly, if  $F_{14}$  is negative, meaning that better workers need less resources, this generates an even stronger force for firm growth. Under NAM, the first effect is the same, but now better firms are matched with worse workers. In this case, firms become exceptionally large if better workers need more resources, meaning that worse workers need less resources.

This suggests clear differences between industries. In some industries such as retail, better firms are those that - amongst other things - have invested heavily in the ability of the management team to supervise many workers. This is achieved through information technology that tells the chain manager exactly how much is in stock, how each cash register is operating, and how each individual employee is performing. In local mom-and-pop stores this is usually not in place to the same degree. Thus, higher firms are associated with a large  $F_{23}$ . Moreover, they tend to employ lower ability workers (which might be partially driven by a large  $F_{23}$ ). So both arguments go in the same directions,  $\mathcal{H}(x)F_{23} + F_{14}$  might be very large, and the difference between the group that is supervised by a single manager in profitable retail chains is much larger than in local mom-and-pop stores.



In other industries such as management consulting or law firms the complementarities in types ( $F_{12}$ ) are very large and matching positive assortative. While it is clearly beneficial for the top managers to have many team members in order to leverage their skills ( $F_{23} > 0$ ), it is also very beneficial to spend time with the very talented team that they assembled to transfer their knowledge ( $F_{14} > 0$ ). In this case firm size changes according to  $\mathcal{H}(x)F_{23} - F_{14}$ , which might be zero or negative, giving an indication why top consultancy firms do not operate much larger groups than lower level ones.

Interestingly, if matching is PAM, distributions are identical, and  $F_{14} = F_{23}$ , then the economy operates as in a one-to-one matching model: the ratio of workers to resources is always one, the assignment and the wages are as in Becker (1973). The reason is that the improvements of the firm in taking on more workers are exactly offset by the advantages of the workers to obtain more resources. Since the size distribution does not vary across types, the remuneration also does not stray from the one that arises if we exogenously imposed a one-to-one matching ratio.

This shows an interesting difference between skill-biased technological change and quantity-biased technological change. Skill-biased technological change in terms of an increase in  $F_{12}$  changes the wages, but might not affect the factor allocations or size distribution. In particular, if the model remains symmetric and remains in the region of positive assortative matching, firms would still remain of unit-size, since both firms benefit from better workers but also better workers benefit from better firms. The wage differences between workers according (14) depend on  $F_1$ , which is larger for higher types when  $F_{12}$  is larger since the role of the firm for one's own wage increase is more important.

In contrast, quantity-biased technological change that increases  $F_{23}$  directly effects the size distribution. Today better firms not only have better managers, but they also invest in resources to supervise. If quantity-biased technological change manifests itself in computing resources that allow to supervise larger groups ( $F_{23}$  larger), then it immediately implies that larger firms are bigger. Such quantity-biased technological change might be more suitable to understand the change in firm sizes and group sizes within firms than the notion of skill-biased technological change.

The importance of the general conditions in (13), (14) and (15) that allow for changes in the firm size due to differentials in the advantages between workers and firms is exactly to highlight the relevant sorting and assignment conditions when substitution between firm and worker inputs takes place and firm size varies across types. For special cases one can analytically construct the equilibrium allocations using these conditions and conduct more careful comparative statics, but more importantly one can exploit the conditions in Proposition 2 to construct an equilibrium in a way that is easily implemented computationally, as shown in the appendix. This hopefully enables the use of two-sided heterogeneity with firm-size-effects in many applied settings.

### 3.3 Special Cases

The following highlights how our model characterizes a number of existing setups that have been heavily used in the literature. It also highlights that it can capture new settings that have not been analyzed before. It also shows that it is not easy to start with certain separability assumptions (for example between the quality and quantity dimensions as in the second example below), because a lot of

formulations in the literature have used different ways of interacting the variables that can be captured in our setup but not in more specialized versions.

**1. Efficiency units of labor.** A particularly common assumption in the literature is the case of efficiency units of labor, where the output remains unchanged as long as the multiplicative term  $xl_x$  remains unchanged. In such a case workers of one type are completely replaceable by workers of half the skills as long as there are twice as many of them. Sorting is then essentially arbitrary: Each firm cares only about the right total amount of efficiency units, but not whether they are obtained by few high-type workers or many low-type workers. Our setup captures efficiency units of labor under production function  $f(x, y, l) = \tilde{f}(y, xl)$ . Taking cross-partials immediately reveals that we always obtain  $F_{12}F_{34} = F_{23}F_{14}$  in this case.

**2. Multiplicative separability.** A particularly tractable case arises under multiplicative separability of the form  $F(x, y, l, r) = A(x, y)B(l, r)$ . In this case the condition (13) for positive assortative matching can be written as  $[AA_{12}/(A_1A_2)][BB_{12}/(B_1B_2)] \geq 1$ . If  $B$  has constant elasticity of substitution  $\varepsilon$ , we obtain an even simpler condition  $AA_{12}/(A_1A_2) \geq \varepsilon$ .<sup>21</sup>

**3. Becker's one-on-one matching model as a limit case.** Consider some output process  $F(x, y, l, r)$ . In the spirit of most of the sorting literature, we can now consider the restricted variant where only "paired" inputs can operate: every worker needs exactly one unit of resource and any resources needs exactly one worker, otherwise it is not used in production. The output can then be represented by  $F(x, y, \min\{l, r\}, \min\{r, l\}) = F(x, y, 1, 1) \min\{l, r\}$ , where the equality follows from constant returns to scale. This nicely corresponds to the multiplicatively separable setup discussed in the previous point. While our framework is built around the idea that more resources or more labor inputs improve production, this Leontief setup on the quantity dimension is exactly the limit case of a CES function with zero elasticity ( $\varepsilon \rightarrow 0$ ). From the previous point we therefore know that sorting arises in this limit if  $F_{12} \geq 0$ , which is exactly the condition in Becker (1973).

**4. Sattinger's and Garicano's span of control problem as a limit cases.** One of the few contributions that provides clear conditions for sorting in a many-to-one matching model is presented in Sattinger (1975). His production function assumes that each worker produces the same, but a worker of type  $x$  needs  $t(x, y)$  units of supervision time from manager of type  $y$ , where better types need to spend less time. The manager can only hire as many workers as he can supervise, so that  $F(x, y, l, r) = \min\{r/t(x, y), l\}$ , where the first terms in the minimization operator captures the number of workers that can be supervised and the second the number of workers hired. Our model allows for more flexibility in the substitution between inputs, but a CES extension that takes  $r/t(x, y)$  and  $l$  as inputs again has the previous Leontief specification as the inelastic limit.<sup>22</sup> Inspecting (13) and taking

<sup>21</sup>If  $\varepsilon$  is in the unit interval, this condition is equivalent to root-supermodularity, i.e., it is equivalent to  $\sqrt[n]{A(x, y)}$  being supermodular with  $n = (1 - \varepsilon)^{-1}$  as shown by Eeckhout and Kircher (2010) in a pairwise matching framework with directed search frictions. If  $\varepsilon > 1$  this requires conditions on  $A(x, y)$  that are stronger than log-supermodularity.

<sup>22</sup>The function  $F(x, y, l, r) = ([rg(x, y)]^{(\varepsilon-1)/\varepsilon} + l^{(\varepsilon-1)/\varepsilon})^{\varepsilon/(\varepsilon-1)}$  approaches  $\min\{rg(x, y), l\}$  as  $\varepsilon \rightarrow 0$ .

the inelastic limit reveals that positive sorting arises only if  $t(x, y)$  is log-supermodular. This exactly recovers the condition found by Sattinger.

Related is Garicano (2000) formulation where each worker can solve problems with difficulty equal to his type, and passes the remaining problems to the supervisor who need one unit of time to answer each problem passed to him. Here the supervision "time"  $t(x)$  depends only on the worker type, but each manager can solve problems up to category  $y$  himself, leading to output  $F = y \min\{r/t(x), l\}$ . Approximating this with the appropriate CES highlights that better managers prefer to hire better workers to leverage their skills.

**5. Extension of Lucas' Span of Control, and Rosen's general production:** Lucas (1978) assumed a production function that is multiplicatively separable in the firm type and the amount of labor, where all labor is identical. Consider the following extension to heterogeneous labor:  $F(x, y, l, r) = yg(x, l/r)r$ , which boils down to  $yg(x, l)$  in the case where all resources are spent on the same worker type. The new condition for assortative matching is  $g_2g_{12} \geq g_1g_{22}$ . If production is increasing in worker type and strictly concave, this means that sorting will be positive unless better workers types indeed dislike to work together because that limits the amount of resources they can obtain ( $g_{12}$  sufficiently negative).

This is related to Rosen's (1982) setup where  $F = h(y)g(x, yl/r)r$  for the first level of supervision and the production workers, which has somewhat different separability assumptions.<sup>23</sup> He allows more flexibility in other parts by allowing for multiple layers of hierarchy and a choice on who performs on which layer. But he analyzes the model only for the case of linear homogeneity of  $g$ , which is equivalent to efficiency units of labor analyzed in point 1 above. Since it is a special case of our setup, our sorting conditions apply directly to this setting. Again, one can easily write the conditions in terms of  $g$ :  $g_{12}/g_1 - g_{22}/g_2 \geq 1/\theta$ , but does not get that much additional insight above and beyond those we have discussed already for the general model.

**6. Spatial Sorting Within the Mono-centric City.** The canonical model of the mono-centric city can explain how citizens locate across different locations, however there is no spatial sorting. All agents are identical and in equilibrium they are indifferent between living in the center or in the periphery by trading off commuting time for housing space and prices.<sup>24</sup> We therefore consider a model of spatial sorting within the city. Let there be a continuum of locations  $y$ , each with housing stock  $r(y)$ . Let  $y \in [0, 1]$ , where  $y$  is the center and  $y$  is the inverse of a measure of the distance from the center. Agents with budget  $x$  have preferences over consumption  $c$  and housing  $h$  represented by a quasi-linear utility function  $u(c, h) = c + v(h)$ . With consumption the numeraire good and  $p_h(y)$  the price per unit of housing in location  $y$ , the budget constraint is  $c + p_h(y)h = xg(y)$ , where  $x$  is the worker skill and  $g(y)$  is

<sup>23</sup>Rosen (1982) equation (1) for the output per worker can be written as  $h(y)\xi(yr/l, x)$  for some functions  $h$  and  $\xi$ , so that total output is constant returns to scale. Output per resource is therefore  $yg(yl/r, x)$  after appropriate transformation (so that  $g(y\theta, x) := \xi(y/\theta, x)/\theta$ ).

<sup>24</sup>Also Lucas and Rossi-Hansberg (2002) model the location of identical citizens but their model incorporates productive as well as residential land use. Though agents are identical, they earn different wages in different locations. The paper proves existence of a competitive equilibrium in this generalized location model which endogenously can generate multiple business centers.

an increasing function representing the time at work rather than in commute. The closer to the center, the less time is spent on commuting and the more time is earned. Then we can write the individual citizen  $x$ 's optimization problem as  $xg(y) + v(h) - p_h(y)h$ . The total supply of housing in location  $y$  is  $r$  and as a result,  $l \cdot h = r$ . Net of the transfers, the aggregate surplus for all  $l$  citizens is given by  $F(x, y, l, r) = xg(y)l + v\left(\frac{r}{l}\right)l$ . It is easily verified that  $F_{12} = g'(y)l$ ,  $F_{34} = -\frac{r}{l}v''\left(\frac{r}{l}\right)$ ,  $F_{14} = 0$  so that if  $v(\cdot)$  is concave there is positive assortative matching of the high income earners into the center and the low income earners in the periphery. A similar functional form is used in Van Nieuwerburgh and Weill (2010) to consider differences between cities rather than within the city, where the term  $xg(y)$  is replaced by a more agnostic worker-output  $u(x, y)$  depending on worker skill  $x$  and city type  $y$ . Sorting is again fully determined by the cross-partial of  $x$  and  $y$  because  $F_{14} = 0$ .

## 4 Extensions

Our baseline model set up is very general. So far, we have given it the interpretation of a managerial assignment problem that optimizes both the worker quality and the firm's span of control. The advantage of the generality of the setup is that we can readily interpret the basic model in different settings and extend it with minor modifications. Our principal extension is the introduction of unemployment. This is then followed by several other interpretations.

### 4.1 Frictions and Involuntary Unemployment

There is no doubt that frictional unemployment is a major ingredient of the labor market. Moreover, in recent years substantially more has been understood about both the determinants of unemployment across heterogeneously skilled agents in the presence of sorting (amongst others Shimer and Smith 2000, Eeckhout and Kircher 2011) and about how unemployment varies across firms of different sizes (Smith 1999, Hawkins 2011, Kaas and Kircher 2010, Menzio and Moen 2010; Garibaldi and Moen forthcoming). Yet, little is known about how unemployment varies in the presence of sorting *and* variation in firm size jointly.

The sorting framework that we laid out in the previous section is well-suited to capture multi-worker firms with decreasing returns in production. In this section we embed a costly recruiting and search process in the previous setup in order to capture the hiring behavior of large firms. This setup builds on the directed search literature (e.g., Peters 1991; Acemoglu and Shimer 1999; Burdett, Shi and Wright 2001; Shi 2001; Shimer 2005; Guerrieri, Shimer and Wright 2010), now with sorting of heterogeneous agents and large firms.

Consider a situation where the workers are unemployed and can only be hired by firms via a frictional hiring process. As part of this process, each firm decides how many vacancies  $v_x$  to post for each worker type  $x$  that it wants to hire. Posting  $v_x$  vacancies has a linear cost  $cv_x$ . It also decides to post wage  $\omega_x$  for this worker type. Observing all vacancy postings, workers decide where to search for a job. Let  $q_x$  denote the "queue" of workers searching for a particular wage offer, defined as the number of workers per vacancy. Frictions in the hiring process make it impossible to fill a position for sure.

Rather, the probability of filling a vacancy is a function of the number of workers queueing for this vacancy, denoted by  $m(q_x)$ , which is assumed to be strictly increasing and strictly concave.<sup>25</sup> Since there are  $q_x$  workers queueing per vacancy, the workers' job-finding rate for these workers is  $m(q_x)/q_x$ . The job finding rate is assumed to be strictly decreasing in the number of workers  $q_x$  queueing per vacancy. Firms can attract workers to their vacancies as long as these workers get in expectation their equilibrium utility, meaning that  $q_x$  adjusts depending on  $\omega_x$  to satisfy:  $\omega_x m(q_x)/q_x = w(x)$ . Note the difference between the wage  $\omega_x$  which is paid when a worker is actually hired, and the expected wage  $w(x)$  of a queueing worker who does not yet know whether he will be hired or not. In equilibrium the firm takes the latter as given because this is the utility that workers can ensure themselves by searching for a job at other firms, while the former is the firm's choice variable with which it can affect how many workers will queue for its jobs. Therefore, a firm maximizes instead of (1) the new problem

$$\begin{aligned} \max_{r_x, \omega_x, v_x} & \int [F(x, y, l_x, r_x) - l_x \omega_x - v_x c] dx \\ \text{s.t. } & l_x = v_x m(q_x); \quad \text{and} \quad \omega_x m(q_x)/q_x = w(x) \end{aligned} \quad (16)$$

and  $r_x$  integrates to unity. The first line simply takes into account that the firm has to pay the vacancy-creation cost, and that the number of hires depends on the amount of hiring per vacancy which is in turn related to the wage that it offers. There are two equivalent representations of this problem that substantially simplify the analysis. It can easily be verified that problem (16) is mathematically equivalent to both of the following two-step problems:

1. Let  $G(x, y, s, r) = \max_v [F(x, y, vm(s/v), r) - vc]$ , and solve  $\max_{s_x, r_x} \int [G(x, y, s_x, r_x) - w(x)s_x] dx$  where  $r_x$  integrates to unity.
2. Let  $C(l, x) = \min_{v, q} [cv + vqw(x)]$  s.t.  $l = vm(q)$ , and solve  $\max_{s_x, r_x} \int [F(x, y, l_x, r_x) - C(l_x, x)] dx$  where  $r_x$  integrates to unity.

In the first equivalent formulation, the firm attracts "searchers"  $s_x$ , which queue up to get jobs at this firm. In order to entice them to do this, it has to offer wage  $w(x)$  in expectation to them whether or not they actually get hired. The definition of  $G$  then reflects the fact that the firm can still decide how many possible vacancies to create for these workers. If the firm creates more vacancies, searchers have an easier time finding a vacancy suitable to them, and this increases the amount of actual labor that is employed within the firm. In the second formulation the firm the output minus the costs of hiring the desired amount of labor. The costs include both the vacancy-creation costs as well as the wage costs, where again the expected wage has to be paid to all workers that are queueing for the jobs.

This has two direct consequences:

1. It has the beauty that  $G$  is fully determined by the primitives, and can be directly integrated into the framework we laid out in Section 2 (where now  $G$  replaces  $F$ ). The firm looks as if it hires

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<sup>25</sup>Careful elaborations how this queueing problem in a finite economy translates into matching probabilities as the population is exanded is given e.g. in Peters (1991) and Burdett, Shi and Wright (2001). It is based on the idea that workers approach vacancies unevenly due to coordination problems, which leads to excess applicants at some vacancies and to few vacancies at others.

"searchers" which have to be paid their expected wage. Applying the machinery from the previous section allows us to assess whether sorting is assortative, and what the expected wages  $w(x)$  are that are paid in equilibrium. We take this formulation embedded in the equilibrium definition of the previous section as the definition of a competitive search equilibrium with large firms.<sup>26</sup>

2. It then relates the expected wages  $w(x)$  that were determined in the previous problem into job finding probabilities of the searchers. Substituting the constraint in Problem 2 into the objective function and taking first order conditions yields the main characterization of this section. It can best be expressed by writing the elasticity of the matching probability as  $\eta(q) := qm'(q)/m(q)$  and by denoting the queue length that solves the minimization problem by  $q(x)$ . We then obtain

$$w(x)q(x) = \frac{\eta(q(x))}{1 - \eta(q(x))}c \quad (17)$$

The right hand side is related to the well-known Hosios condition (Hosios, 1990), which showed that efficient vacancy creation is related to the elasticity of the matching function. The condition becomes particularly tractable in commonly used settings in which the elasticity is constant. In this case the queue length that different workers face is inverse proportional to the expected utility that they obtain in equilibrium. Since better workers obtain higher expected utility  $w(x)$  as determined in Problem 1 (otherwise a firm could higher better workers at equal cost), they face proportionally lower competition for each job and correspondingly higher job finding probabilities. This arises because the opportunity costs of having high skilled workers unsuccessfully queue for employment is higher, and therefore firms are more willing to create enough vacancies to enable most of these applicants to actually get hired for the job. The logic applies even if the elasticity is not constant:

**Proposition 4** *Assume higher worker types create more output ( $F_x > 0$ ). In the competitive search equilibrium with large firms, higher skilled workers have face lower unemployment rates.*

**Proof.** The term  $\eta(q)/[q(1 - \eta(q))] = m'(q)/[m(q) - qm'(q)]$ . This term is strictly decreasing in  $q$ , since the numerator is strictly decreasing and the denominator is strictly increasing in  $q$ . Since output at any firm is increasing in skill ( $F_x > 0$ ) it follows immediately that in any equilibrium  $w(x)$  is increasing in  $x$ . Implicit differentiation of (17) implies that  $q(x)$  is decreasing, which in turn implies that the chances of finding employment are increasing in  $x$ . ■

Interestingly, this implies that under positive assortative matching the firm-size can be increasing in firm type even though the number of workers that apply for jobs is decreasing. This can be seen mathematically as follows. The amount of labor that is actually hired,  $l(x)$ , relates to the actual number of searchers and their queue per vacancy as  $l(x) = s(x)m(q(x))/q(x)$ , implying:

$$l'(x) = s' \frac{m}{q} + s \frac{m'q - m}{q^2} q'.$$

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<sup>26</sup>The same mathematical structure arises (after rearranging) when we start with an equilibrium definition in the natural way that is usually used in the competitive search literature, where firms compete in actual wages and not in terms of expected wage payments.

The change in the number of searchers ( $s'$ ) is determined by (14) under appropriate change of variables ( $\theta$  and  $f$  replaced by  $s$  and  $g$ ). Even if the number of workers that search for employment at better firms is not increasing, the number of hires might still be increasing because the second term is strictly positive. This may be due to the fact that high productivity firms put more resources into creating jobs for their high-skilled applicants. Recruiting of talented lawyers at a law firm is likely to involve more resources, either the direct cost or the opportunity cost of time, than what is spent on hiring low skilled labor at a fast food restaurant.

Instead, the vacancy rate across firms of different sizes is ambiguous.

**Proposition 5** *The vacancy rate is ambiguous in firm size.*

**Proof.** Consider PAM (likewise for NAM). The vacancy rate ( $1/q$ ) is increasing in  $x$ , and under PAM then also in  $y$ . However, from Proposition 3, firm size ambiguous in  $y$ . In particular, it is increasing if  $F_{23} \geq F_{14}$  and decreasing if  $F_{23} \leq F_{14}$ . ■

This result immediately stems from the fact that firm size in general is ambiguous in firm type  $y$ .

## 4.2 Capital Investment

Consider a production process that not only takes as inputs the amount of labor and of proprietary firm resources, and creates output  $\hat{F}(x, y, l, r, k)$ . The generic capital  $k$  that can be bought on the world market at price  $i$ . Optimal use of resources requires  $F(x, y, l, r) = \max_k [\hat{F}(x, y, l, r, k) - ik]$ , where  $F$  is constant returns in its last two arguments if  $\hat{F}$  is constant returns in its last three arguments. Rewriting the cross-margin-complementarity condition (13) in terms of the new primitive yields the following condition for positive assortative matching:  $\hat{F}_{12}\hat{F}_{34}\hat{F}_{55} - \hat{F}_{12}\hat{F}_{35}\hat{F}_{45} - \hat{F}_{15}\hat{F}_{25}\hat{F}_{34} \geq \hat{F}_{14}\hat{F}_{23}\hat{F}_{55} - \hat{F}_{14}\hat{F}_{25}\hat{F}_{35} - \hat{F}_{15}\hat{F}_{23}\hat{F}_{45}$ .

## 4.3 Monopolistic Competition

In the previous sections, we analyzed the case where the firm's output is converted one-for-one into agents utility. Therefore, there are no consequences on the final output price of the good, which is normalized to one. An often used assumption in the trade literature concerns consumer preferences pioneered by Dixit and Stiglitz (1977) which are CES with elasticity of substitution  $\rho \in (0, 1)$  among the goods produced by different firms. For these preferences it is well-known that a firm that produces output  $\tilde{f}$  has achieves a sales revenues  $\chi \tilde{f}^\rho$ , where  $\chi$  is an equilibrium outcome that is viewed as constant from the perspective of the individual firm.<sup>27</sup> The difficulty in this setup is that, despite the fact that output is constant returns to scale in employment and firm resources, the revenue of the firm has decreasing returns to scale. Therefore, we cannot directly apply (13). But we can conjecture that

<sup>27</sup>The underlying form for the utility function is  $U = x_0^{1-\mu} (\int c(y)^\rho dy)^{\mu/\rho}$ , where  $x_0$  is a numeraire good and  $c(y)$  is the amount of consumption of the good of producer  $y$ . Then one obtains  $\chi = (\mu Y)^{1-\rho} P^\rho$  where  $Y$  is the aggregate income,  $p_y$  denotes the price achieved by firm  $y$  through its equilibrium quantity, and  $P = \left( \int p_y^{\rho/(1-\rho)} \right)^{\rho/(1-\rho)}$  represents the aggregate price index.

there is assortative matching so that the firm employs only one worker type, in which case revenues are  $f(x, y, l) = \chi \tilde{f}(x, y, l)^\rho$ , and we can apply (10) directly. Rearranging and using  $\tilde{F}(x, y, l, r) = r \tilde{f}(x, y, l/r)$  we get the condition for positive assortative matching

$$\begin{aligned} & \left[ \rho \tilde{F}_{12} + (1 - \rho) \tilde{F} \frac{\partial^2 \ln \tilde{F}}{\partial x \partial y} \right] \left[ \rho \tilde{F}_{34} - (1 - \rho) l \tilde{F} \frac{\partial^2 \ln \tilde{F}}{\partial l^2} \right] \\ \geq & \left[ \rho \tilde{F}_{23} + (1 - \rho) \tilde{F} \frac{\partial^2 \ln \tilde{F}}{\partial y \partial l} \right] \left[ \rho \tilde{F}_{14} + (1 - \rho) \left( l \tilde{F}_{13} - l \tilde{F} \frac{\partial^2 \ln \tilde{F}}{\partial x \partial r} \right) \right]. \end{aligned}$$

Several points are note-worthy. First, the condition is independent of  $\chi$ , and therefore can be checked before this term is computed as an outcome of the market interaction. Furthermore, for elastic preferences ( $\delta \rightarrow 1$ ) the condition reduces to our original condition (13). In general, the condition relies not only on supermodularities in the production function, but also on log-supermodularities. This should not be surprising. Even in the standard models supermodularity is the relevant condition when the marginal consumption value of output is normalized to one (Becker 1973), while sorting when output is CES-aggregated requires log-supermodularity. If  $\tilde{F}$  is multiplicatively separable between quantity and quality dimension, and the quality dimension is CES, then as the quality dimension becomes increasingly inelastic it is easy to show that the condition reduces to log-supermodularity in  $x$  and  $y$ .

#### 4.4 Optimal transportation

Assume it costs  $-r \cdot c(x, y)$  to move a  $r$  units of waste from production site  $x$  into destination storage  $y$ , and if one attempts to move more units  $r$  into any given amount  $l$  of storage then there is some probability of damage  $d(r/l)$  that each unit that is stored gets destroyed. This leads to function  $F(x, y, l, r) = -rc(x, y) - \alpha rd(r/l)$ , where  $\alpha$  represents the lost revenue because of destruction. Unlike in the standard Monge-Kantorovich transportation problem, here the allocation need not occur in fixed quantities.<sup>28</sup>

#### 4.5 Endogenous type distributions, technology choice, and team-work

One way to endogenize the type distribution is to assume that there is free entry of firms (free entry of resources in the model), but entry with type  $y$  costs  $c(y)$ . If output is increase in  $y$ , i.e.,  $F_2 > 0$ , then it is crucial for a meaningful entry decision that  $c(y)$  is strictly increasing. If  $c$  is increasing and differentiable, and our sorting condition is satisfied everywhere, it is not difficult to construct an equilibrium where the profits of firms according to (2) equal the entry cost  $c(y)$  for all active firms. In fact, this formulation is easier to construct: We know that the highest types match, so that  $\mu(\bar{x}) = \bar{y}$ . The problem is usually how to determine at which ratio they match, i.e., to find  $\theta(\bar{x})$ . But here it is given simply by requirement that the profits of the highest firm equals the entry costs. Substituting the

<sup>28</sup> Observe that in the Monge-Kantorovich problem the allocation need not be in pure strategies. The optimal allocation may involve mixing or in large populations there may be a fraction of agents of a given type allocated to one location and the remainder to another location as long as the total measure of agents at any location does not exceed one. What differs here is the intensive margin. Any location is not restricted to taking on a given measure of agents.



first order condition (5) into the objective function yields profit  $f(\bar{x}, \mu(\bar{x}), \theta(\bar{x})) - \theta(\bar{x})f_{\theta}(\bar{x}, \mu(\bar{x}), \theta(\bar{x}))$ , which have to equal  $c(\mu(\bar{x}))$ . This can be then used together with the first order conditions and the differential equations in (2) to construct the type distribution after entry at all lower types.

More complicated is the analysis when one considers a common pool of workers, some of whom choose to be managers while others choose to remain workers. This is then a teamwork problem, where one team becomes the  $y$ 's and the other the  $x$ 's. While interesting, we leave this analysis for further work.

## 5 Concluding Remarks

We have proposed a matching model that incorporates factor intensity and unemployment. We derive a simple condition for assortative matching and characterize the equilibrium firm size, unemployment level and unemployment by skills.

## 6 Appendix

### Remaining Proof of Proposition 1

**Proof.** Part I: sufficiency. Focus on positive assortative matching. The same logic applies to negative assortative matching. Strict cross-margin-supermodularity  $F_{12}F_{34} > F_{14}F_{23}$  for all  $(x, y, l, r)$  is by (10) equivalent to  $f_{\theta\theta}f_{xy} - f_{y\theta}f_{x\theta} + f_{y\theta}f_x/\theta < 0$  for all  $(x, y, \theta)$ . Assume a feasible resource allocation  $\mathcal{R}$  such that  $(x_i, y_i, \theta_i) \in \text{supp}\mathcal{R}$  for  $i \in \{1, 2\}$  and  $x_1 > x_2$  but  $y_1 < y_2$ . Since  $\mathcal{R}(x, y, 0) = 0$ , that means that  $\theta_i > 0$ . If not, by the fact that  $(x_i, y_i, \theta_i) \in \text{supp}\mathcal{R}$  implies that there is a closeby combination with positive intensity. Let  $r_i$  denote the measure of resources at combination  $(x_i, y_i, \theta_i)$ . If the type distribution has mass-points, this is exactly the measure of types assigned to this combination. We will consider this case here. (If the type distribution only has a density, then it is the mass of resources in an arbitrarily small area around  $(x_i, y_i, \theta_i)$ . By continuity all resources in this area have output very close to  $f(x_i, y_i, \theta_i)$ , and since the inequalities below are strict, the argument applies also to this case.)

We will establish that output is strictly increased under a feasible variation yielding resource allocation  $\mathcal{R}'$  that pairs some of the  $x_2$  workers to some of the  $y_2$  resources. We proceed in two steps. Step 1 has the key insight. Subsequently, Part II will establish necessity.

#### 1. Establish the marginal benefit from assigning additional workers to some resource type:

Consider some  $(x, y, \theta)$  such that  $r$  resources are deployed in this match (and are paired to  $\theta r$  workers). For the variational argument, we are interested in the marginal benefit of pairing an additional measure  $r'$  of resources of type  $y'$  with workers of type  $x$ . The optimal output is generated by withdrawing some optimal measure  $\theta' r'$  of the workers that were supposed to be working to with resource  $y$  and reassigning them to work with resource  $y'$ . The joint output at  $(x, y)$  and  $(x, y')$  is given by

$$r f(x, y, r, \theta - \theta' r' / r) + r' f(x, y', \theta'). \quad (18)$$

Optimality of  $\theta'$  requires according to the first order condition that  $f_3(x, y, \theta - \theta' r' / r) = f_3(x, y', \theta')$ , which shows that the optimal  $\theta'$  is itself a function of  $r'$ . Denote  $\beta(y'; x, y, \theta)$  the marginal increase of (18) from increasing  $r'$ , evaluated at  $r' = 0$ . It is given by

$$\beta(y'; x, y, \theta) = f(x, y', \theta') - \theta' f_3(x, y', \theta') \quad (19)$$

$$\text{where } \theta' \text{ is determined by } f_3(x, y', \theta') = f_3(x, y, \theta). \quad (20)$$

The constrained (20) reiterates the optimality of  $\theta'$  as a function of  $x, y, \theta$  and  $y'$ . The cross-partial  $\beta_{12}$  of the marginal benefit in (19) with respect to  $x$  and  $y'$  is strictly positive, evaluated at  $y' = y$ , iff

$$f_{xy} > -[\theta f_{y\theta} f_{x\theta} + f_{y\theta} f_x] / [\theta f_{\theta\theta}],$$

i.e., exactly when our cross-margin condition holds. Therefore, it is optimal to assign higher buyers to higher sellers locally around  $(x, y)$ . This is at the heart of the argument. The next step simply extends this logic to a global argument where  $y'$  might be far away from  $y$ .

#### 2. Not PAM has strictly positive marginal benefits from matching the high types:

We started under the assumption that matching is not assortative since  $x_1 > x_2$  but  $y_1 < y_2$ . In particular, consider  $y_1$  matched to  $x_2$  at queue length  $\lambda_1$  and  $y_2$  matched to  $x_1$  at queue  $\lambda_2$ , where  $x_2 > x_1$  and  $y_2 > y_1$ . For  $(x_1, y_2)$  and  $(y_1, x_2)$  to be matched, optimality requires that the marginal benefit of types  $y^v = y_1$  are higher when paired with  $x_2$ , while types  $y^v = y_2$  yield higher benefit when

paired with  $x_1$  :

$$\beta(y_1; x_2, y_2, \theta_2) \leq \beta(y_1; x_1, y_1, \theta_1), \quad (21)$$

$$\beta(y_2; x_2, y_2, \theta_2) \geq \beta(y_2; x_1, y_1, \theta_1), \quad (22)$$

where  $\beta(\cdot; \cdot, \cdot, \cdot)$  was defined in (18). We will show that if (21) holds, then (22) cannot hold, which yields the desired contradiction. We will show this by proving that the benefit  $\beta(y'; x_1, y_1, \theta_1)$  on the right hand side of (21) and (22) always remains above the benefit  $\beta(y'; x_2, y_2, \theta_2)$  on the left hand side. By (21) this has to be true at  $y' = y_1$ , and we will show that it remains true when we move to higher  $y'$ . The marginal increase of  $\beta$  with respect to its first argument  $y'$  is given by

$$\beta_1(y^v; x, y, \lambda) = f(x, y', \theta'), \quad (23)$$

where  $\theta'$  is again determined as in (20). Assume there is some  $y' \geq y_1$  such that marginal benefits are equalized, i.e.,  $\beta(y'; x_2, y_2, \theta_2) = \beta(y'; x_1, y_1, \theta_1)$ . We have established the result when we can show that  $\beta_1(y'; x_2, y_2, \theta_2) < \beta_1(y'; x_1, y_1, \theta_1)$ .

By (23) this equivalent to showing that  $f(x_2, y', \theta'_2) < f(x_1, y', \theta'_1)$ , where  $\theta'_1 = \theta'(y'; x_1, y_2, \lambda_2)$  and  $\theta'_2 = \theta'(y'; x_2, y_1, \lambda_1)$  as in (20). To show this, define  $\xi(x)$  for all  $x$  in resemblance of (19) by the following equality

$$f(x, y', \xi(x)) - \xi(x)f_3(x, y', \xi(x)) = \beta(y'; x_2, y_2, \theta_2),$$

which implies  $\xi(x_2) = \theta'_2$  and  $\xi(x_1) = \theta'_1$  by equality of the marginal benefits at  $y'$ , i.e. by  $\beta(y'; x_2, y_2, \theta_2) = \beta(y'; x_1, y_1, \theta_1)$ . Differentiating  $f(x, y', \xi(x))$  with respect to  $x$  reveals that it is strictly increasing exactly under our strict inequality  $f_{\theta\theta}f_{xy} - f_{y\theta}f_{x\theta} + f_{y\theta}f_x/\theta < 0$ . This in turn implies  $f(x_2, y', \theta'_2) < f(x_1, y', \theta'_1)$ .

Part II: necessity. Assume that (13) fails at some  $(x', y', l'', r'')$ . By continuity it also fails at some  $(x', y', l', r')$  with  $l' > 0$  and  $r' > 0$  sufficiently close to  $(x', y', l'', r'')$ . Then it also fails at  $(x', y', \theta', 1)$  for  $\theta' = l'/r'$  (see also Footnote 18). By continuity, this means that  $F_{12}F_{34} < F_{23}F_{14}$  for all  $(x, y, \theta, 1) \in N$ , where  $N$  is a small enough open neighborhood of  $(x', y', \theta', 1)$ . If we can restrict the equilibrium allocation to lie in  $N$ , then by the analogy of the preceeding section for negative assortative matching we know that matching can only be negative assortative, and therefore (13) cannot fail if we want to obtain positive assortative matching. Since we want to ensure positive assortative matching for all type distributions, we can choose the support of  $x$  and  $y$  within this neighborhood. But since  $\theta$  is endogenous, this requires slightly more work. Assume that  $X = [x', x' + \varepsilon]$  and  $Y = [y', y' + \varepsilon]$ , and uniform type distributions with mass  $H_w^\varepsilon(x' + \varepsilon) = \theta'$  and  $H_f^\varepsilon(y' + \varepsilon) = 1$ . For small enough  $\varepsilon'$ , firms make nearly identical profits. Since they can only match with nearly identical types, identical profits imply that they have to have nearly identical factor ratios  $\theta(x)$ . These have to be close to the average ratio in the population. Therefore, for  $\varepsilon$  small enough all matches lie in  $N$ , which rules out that matching can be positive assortative for all type distributions if (13) fails. ■

## 6.1 Construction of a differential positive assortative equilibrium.

Assume (13) holds at all  $(x, y, l, r) \in \mathbb{R}_+^4$ . Assume also that  $F(x, y, \theta, 1)$  is strictly increasing in  $x$  and  $y$  and has a finite strictly positive maximum in  $\theta$  (for example because of positive outside options as in outlined in Footnote 10). The former implies that implies that higher types are matched in equilibrium whenever lower types are. We know there is sorting, so  $\mu(\bar{x}) = \bar{y}$ . Take a guess for  $\theta(\bar{x})$ . Then the first two equations in (14) evaluated at  $(x, \mu(x), \theta(x))$  give a differential equation system that uniquely gives  $\mu(x)$  and  $\theta(x)$  at all values of  $x$  below  $\bar{x}$ . Equation (5) gives the associated wages  $w(x)$ , and output

minus the wages gives the firms' profits  $\pi(\mu(x))$ . Stop the differential equation at  $x^*$  and  $y^* = \mu(x^*)$  when for the first time one of the following conditions occurs: (a)  $x^* = \underline{x}$ , (b)  $y^* = \underline{y}$ , (c)  $w(x^*) = 0$  or (d)  $\pi(y^*) = 0$ . One has found an equilibrium if of the following holds: (a)&(b) which means that the lowest types are matched and might both get positive payoff, (a)&(d) which means that not all firms are matched which means that the lowest firms have unmatched immediate substitutes and therefore have to earn zero, or (b)&(c) in which case some workers are unmatched and the lowest worker type gets zero, or (c)&(d) hold in which case there are both unmatched workers and firms at the lower end. Clearly, the first order conditions are satisfied because the differential equation was constructed to satisfy (5) and (6), and the second order condition is locally satisfied because (13) holds. One can show that (13) also implies that no firm wants to deviate globally. Finally, for any guess of  $\theta(\bar{x})$  such that  $w(\bar{x}) > 0$  and  $\pi(\bar{y}) > 0$  one of the end-point conditions (a) – (d) arises. At very low guesses either (b) or (d) holds (few workers per firm means that one either exhausts the firms or depletes their profits), while at very high levels of  $\theta(\bar{x})$  either (a) or (c) holds. Since the system changes continuously in the initial guess, the set of guesses that gives rise to a particular condition is compact. Given that at low guesses (b) or (d) hold while at high guess (a) or (c) hold, there has to be some intermediate guess where two conditions hold at the same time: (a)&(b), (a)&(d), (b)&(c) or (c)&(d), constituting an equilibrium.

## The Non-Homogeneous Production Technology

Let output of the firm be  $F(x, y, r, s)$ , and the firm of type  $y$  chooses the worker type and the labor intensity  $l$ . As before, let the capital intensity  $r$  be given. Then the problem is

$$\max_{x, l} F(x, y, l, r) - lw(x) - rv(y).$$

The first order conditions for optimality are

$$\begin{aligned} F_1(x, \mu(x), l, r) - lw'(x) &= 0 \\ F_3(x, \mu(x), l, r) - w(x) &= 0 \end{aligned}$$

where  $\mu(x)$  and  $l$  are the equilibrium values. The second order condition of this problem requires the Hessian  $H$  to be negative definite:

$$H = \begin{pmatrix} F_{11} - rw'' & F_{13} - w' \\ F_{13} - w' & F_{33} \end{pmatrix}$$

which requires that all the eigenvalues are negative or equivalently,  $F_{11} - rw'' < 0$  (which follows from concavity in all the arguments  $(x, y, l, r)$ ), and

$$\begin{vmatrix} F_{11} - rw'' & F_{13} - w' \\ F_{13} - w' & F_{33} \end{vmatrix} > 0.$$

After differentiating the two FOCs along the equilibrium allocation to substitute for  $F_{11} - rw'' = -F_{12}\mu'$  and  $F_{13} - w' = -F_{23}\mu'$  and also using the first FOC to rewrite  $w' = F_1/r$  we get

$$\begin{vmatrix} -F_{12}\mu' & -F_{23}\mu' \\ F_{13} - w' & F_{33} \end{vmatrix} > 0$$

or  $-F_{12}F_{33}\mu' + (F_{13} - F_1/r)F_{23}\mu' > 0$  and thus PAM requires (knowing that  $F_{33} < 0$ )

$$F_{12} > \frac{(F_1/r - F_{13})F_{23}}{|F_{33}|}.$$

Observe that this condition is similar to the one we obtained for the homogeneous case, only that now it depends on the marginal product  $F_1$  and the concavity of  $F$  in  $l$ ,  $F_{33}$ . Clearly, the production function has increasing returns, then the firm will only choose one type and levy all its resources on this type.

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